

Superconducting $\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_{4-y}$ Bicrystal Grain Boundary Josephson Junctions

S. Kleefisch, L. Alff^{a)}, U. Schoop, A. Marx, and R. Gross

II. Physikalisches Institut, Universität zu Köln, Zùlpicherstr. 77, D - 50937 Köln, Germany

M. Naito and H. Sato

NTT Basic Research Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243, Japan

(received January 15, 1998)

We have studied the electric transport properties of symmetrical [001] tilt $\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_{4-y}$ (NCCO) bicrystal grain boundary Josephson junctions (GBJs) fabricated on SrTiO_3 bicrystal substrates with misorientation angles of 24° and 36.8° . The superconducting properties of the NCCO-GBJs are similar to those of GBJs fabricated from the hole doped high temperature superconductors (HTS). The critical current density J_c decreases strongly with increasing misorientation angle. The products of the critical current I_c and the normal resistance R_n ($\sim 100 \mu\text{V}$ at 4.2 K) are small compared to the gap voltage and fit well to the universal scaling law $I_c R_n \propto \sqrt{J_c}$ found for GBJs fabricated from the hole doped HTS. This suggests that the symmetry of the order parameter, which most likely is different for the electron and the hole doped HTS has little influence on the characteristic properties of symmetrical [001] tilt GBJs.

PACS: 74.25.Fy, 74.50.+r

Bicrystal grain boundary Josephson junctions (GBJs) have been studied intensively using epitaxial thin films of the various hole doped high temperature superconductors (HTS) [1–3]. However, there is very limited information on GBJs fabricated from the electron doped material $\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_{4-y}$ (NCCO) [4]. For the vast majority of GBJs the transport properties can be well described within the intrinsically shunted junction (ISJ) model [2,5,6]. In this model a continuous, but spatially inhomogeneous insulating grain boundary barrier is assumed that contains a high density of localized defect states. The localized states allow for resonant tunneling of quasiparticles providing an intrinsic resistive shunt, whereas resonant tunneling of Cooper pairs is prevented by Coulomb repulsion. This results in reduced $I_c R_n$ products and a scaling behavior $I_c R_n \propto \sqrt{J_c}$ observed in many experiments [2,5–7]. Meanwhile, it is well established that most hole doped HTS have a dominant d -wave component of the order parameter (OP) [8]. The influence of the d -wave symmetry of the OP on the magnetic field dependence of I_c has been shown for asymmetric 45° tilt YBCO-GBJs [9]. So far, in the ISJ-model the likely d -wave pairing state of the hole doped HTS has not been taken into account and the relevance of the d -wave symmetry of the OP for the characteristic properties of symmetrical [001] tilt GBJs such as the small value and the scaling behavior of the $I_c R_n$ product is still a point of controversy. To clarify this issue we have studied [001] tilt NCCO-GBJs. Since for the electron doped material NCCO there is convincing experimental evidence for a s -wave symmetry of the OP [10–13], NCCO-GBJs represent an interesting model system to test the influence of the OP symmetry on the transport properties of GBJs.

The NCCO-GBJs were fabricated by molecular beam epi-

taxy (MBE) of c -axis oriented NCCO thin films on SrTiO_3 bicrystal substrates. The substrate temperature during growth was about 730°C and ozone was used as oxidation gas. For the critical temperature T_c , the resistivity $\rho(250 \text{ K})$, and $\rho(25 \text{ K})$ typical values of 23 – 24 K, $350 \mu\Omega\text{cm}$, and $50 \mu\Omega\text{cm}$ were obtained, respectively. A detailed description of the fabrication process was given by Naito *et al.* [14,15]. For NCCO-GBJs the film quality is a key issue, since small deviations from optimum (preferentially oxygen stoichiometry) can reduce I_c to unmeasurably small values. More precisely, for small I_c the Josephson coupling energy E_J becomes comparable to or even smaller than the thermal energy $k_B T$. This may be the reason why until now a finite I_c has been observed only for low angle ($\leq 10^\circ$) NCCO-GBJs [4]. For our samples the direct observation of a critical current was possible only for the 24° tilt GBJs having J_c values between 5 and 50 A/cm^2 at 4.2 K. For the 36.8° tilt GBJs the J_c values are more than an order of magnitude smaller preventing the direct measurement of I_c due to thermal noise effects ($E_J < k_B T$). Although we cannot give any functional dependence at present, our data clearly show that J_c strongly decreases with increasing misorientation angle.

Fig. 1 shows a typical resistive transition of a NCCO-GBJ. The onset temperature of 24 K marks the resistive transition of the NCCO film. The foot structure emerging below about 90Ω is close to resistance $R_p(T) = R_n(T) \left[I_0 \left(\frac{\hbar I_c(T)}{2ek_B T} \right) \right]^{-2}$, expected for ideal overdamped Josephson junctions due to thermally activated phase slip-page (TAPS) [16,17]. Here, I_0 is the modified Bessel function of the first kind. As shown by Fig. 1, the TAPS model qualitatively describes the measured foot structure using $R_n(T) = \text{const.} = 90 \Omega$ and $I_c(T) = I_c(0)(1 - T/T_c)^2$.

^{a)}e-mail: alff@ph2.uni-koeln.de

Certainly, a better fit is possible by taking into account a temperature dependent R_n and a modified $I_c(T)$ dependence. The normal resistance times junction area, ρ_n , of the 24° tilt GBJs ranged between 1.5 and $8 \times 10^{-6} \Omega \text{cm}^2$ and was more than an order of magnitude larger for the 36.8° tilt GBJs.

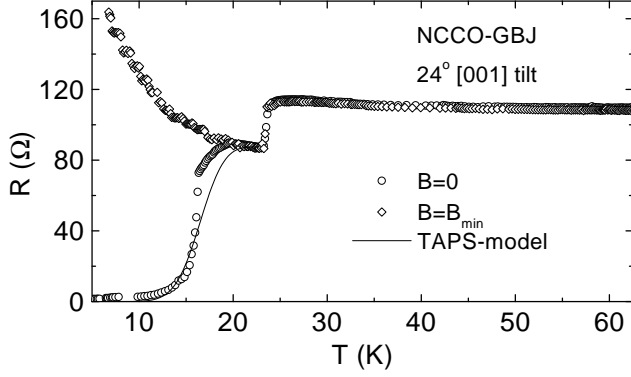


FIG. 1. Resistance vs. temperature curve of a symmetrical 24° [001] tilt NCCO bicrystal GBJ ($W=10 \mu\text{m}$) for $B=0$ and $B=B_{\min}$. The solid line shows the prediction of the RSJ-model including thermal noise [16,17].

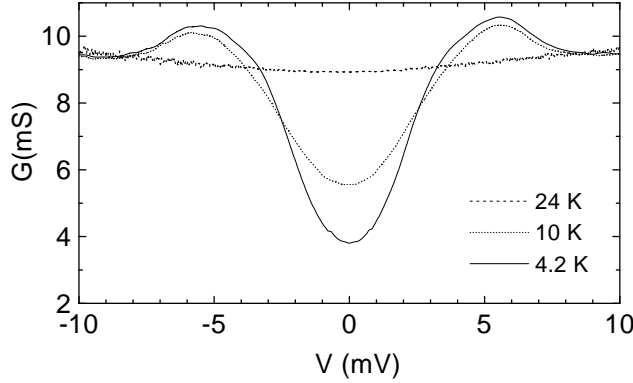


FIG. 2. Conductance versus voltage curves of a 24° [001] tilt NCCO bicrystal GBJ at different temperatures.

Fig. 2 shows the $G(V) = dI(V)/dV$ curves of a NCCO-GBJ. The Josephson current was suppressed by applying a small magnetic field B_{\min} corresponding to a minimum of the $I_c(B)$ dependence of the GBJ. A clear gap structure is observed in the $G(V)$ curves with a gap voltage $V_g = \Delta_0/e$ [18] of about 6 mV that is comparable to values reported in literature [11,12,19,20]. The observation of a clear gap structure and the temperature independent conductance well above V_g strongly suggest that the dominating transport mechanism in the NCCO-GBJs is elastic tunneling. That is, in agreement to what is observed for YBCO-, LSCO- and BSCCO-GBJs [2,21], also for the NCCO-GBJs the dominant transport mechanism most likely is elastic tunneling via a single localized state. Assuming purely elastic resonant tunneling a density of localized states $n_{\text{res}} = \hbar/2e^2\rho_n \approx 1 \times 10^{14} \text{ m}^{-2}$ can be estimated which is close to values reported recently [21]. We also note that in contrast to GBJs fabricated from the hole doped HTS, the $G(V)$ curves of the NCCO-GBJs show no zero bias conductance peak which is consistent with a s -wave symmetry of the OP in NCCO [19]. We note, however, that the OP of

NCCO may be highly anisotropic, i.e., the amplitude of the OP may show a strong k -dependence but there is no sign change as for a d -wave OP.

Suppressing I_c by applying $B = B_{\min}$ we have $\hbar I_c(B)/2ek_B T \ll 1$ and, hence, $R_p(T) \simeq R_n(T)$, i.e., $R_n(T)$ can be measured directly. The result is shown in Fig. 1 for a 24° tilt GBJ. A very similar result is obtained for the 36.8° tilt GBJs even for $B=0$, since here $\hbar I_c(B)/2ek_B T \ll 1$ even at zero field. It is evident that R_n increases strongly with decreasing temperature. We emphasize that this increase of R_n cannot be caused by the presence of inelastic tunneling processes freezing out on going to lower temperatures, since the dominating transport mechanism is elastic tunneling as discussed above. In order to discuss the origin of the observed $R_n(T)$ dependence we have to take into account that R_n corresponds to dV/dI at $V \simeq 0$. Provided that the OP of NCCO has an s -wave symmetry, a strong reduction of the density of states below V_g is expected going to low T resulting in an increase of the dV/dI at small V . We note that an almost T independent R_n has been observed for most GBJs fabricated from the hole doped HTS [2,21]. This difference may be related to a different OP symmetry in the electron and hole doped HTS. It is likely that for the latter a d -wave symmetry of the OP together with pair breaking effects at surfaces of d -wave superconductors cause a large and weakly T dependent density of states around the Fermi level and, hence, a weakly T dependent R_n .

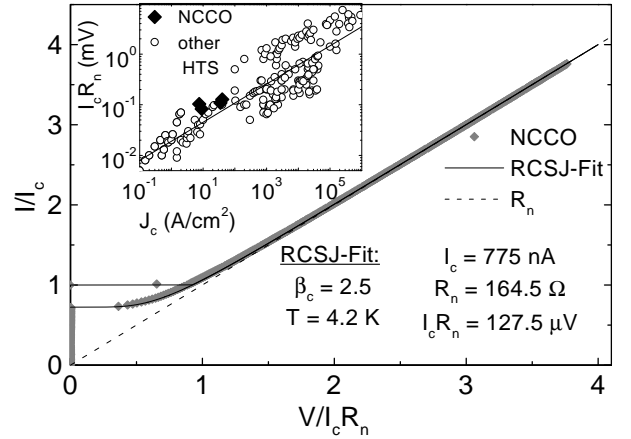


FIG. 3. Current vs. voltage of a $10 \mu\text{m}$ wide, 24° [001] tilt NCCO bicrystal GBJ. Also shown is the RCSJ-model prediction (solid line) and the ohmic line (broken line). In the inset, the $I_c R_n$ products of NCCO-GBJs (full symbols) are plotted vs. J_c together with $I_c R_n$ products of YBCO- and BSCCO-GBJs (bicrystal, step-edge, biepitaxial) taken from Ref. [2] (open symbols).

A typical IVC of a NCCO-GBJ is shown in Fig. 3. Due to the small J_c and large ρ_n values of NCCO-GBJs, for a typical junction size of a few μm^2 typical I_c and R_n values are below $1 \mu\text{A}$ and above 100Ω , respectively, at 4.2 K resulting in $I_c R_n$ products around $100 \mu\text{V}$ small compared to V_g . At 4.2 K the IVC is slightly hysteretic. Within the resistively and capacitively shunted junction (RCSJ) model [22] a good fit is obtained for a McCumber-parameter $\beta_C \simeq 2.5$. We also note that the IVCs of NCCO-GBJs show no excess

current. The inset of Fig. 3 clearly shows that the NCCO-GBJs fit well to the general scaling relation $I_c R_n \propto (J_c)^q$ with $q \approx 0.5 \pm 0.1$ found for hole doped HTS [2]. This strongly suggests that the mechanism of charge transport across the grain boundary barrier is similar for the hole and electron doped materials. Furthermore, since NCCO likely has a dominating s -wave and the hole doped HTS a dominating d -wave component of the OP, the symmetry of the OP can be ruled out as a main cause for the small value and the scaling relation of the $I_c R_n$ product. A similar argument holds for the strong decrease of J_c with increasing misorientation angle. The similarity of the transport properties of GBJs fabricated from the electron and hole doped HTS can be naturally explained within the ISJ-model [2,5,6]. Here, the small $I_c R_n$ values and the scaling behavior is explained by the fact that for both NCCO-GBJs and those fabricated from the hole doped HTS the main transport mechanism is resonant tunneling via localized states within an insulating grain boundary barrier for the quasiparticles and direct tunneling for the Cooper pairs.

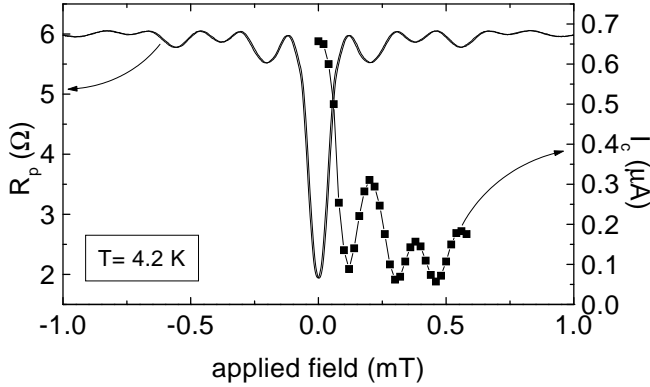


FIG. 4. Magnetic field dependence of the critical current of a 24° [001] tilt NCCO-GBJ at 4.2 K. Solid symbols: I_c values directly obtained from IVCs. Solid line: $I_c(B)$ curve derived from $R_p(B)$.

Fig. 4 shows the magnetic field dependence of the critical current. The solid symbols represent the $I_c(B)$ data obtained by determining I_c directly from the IVCs. The solid line shows $R_p(B)$. Since at constant temperature $R_p(B) = R_n \left[I_0 \left(\frac{\hbar I_c(B)}{2e k_B T} \right) \right]^{-2}$ is determined only by $I_c(B)$, the field dependence of I_c can be derived from the measured $R_p(B)$ dependence by inverting the Bessel function [23]. The quantitative agreement is good and Fig. 4 shows that both methods give the same modulation period as expected [23]. The observed $I_c(B)$ pattern is perfectly symmetric about $B = 0$ and close to a Fraunhofer diffraction pattern expected for small Josephson junctions with spatially homogeneous J_c . This suggests that J_c is homogeneous along the grain boundary on a μm scale.

In conclusion, the superconducting properties of symmetric [001] tilt GBJs fabricated from both the hole and electron doped HTS are very similar and can be well described within the ISJ-model. In particular, the scaling law $I_c R_n \propto \sqrt{J_c}$ as well as the strong decrease of J_c with increasing misorientation angle found for the hole doped HTS also holds for NCCO-GBJs. Provided that the OP symmetry of electron

and hole doped HTS is s and d -wave, respectively, this suggests that the grain boundary properties are not strongly influenced by the symmetry of the OP but are dominated by the structural properties of the grain boundary barrier that may be similar for both materials.

The authors acknowledge valuable discussion with J. Halbritter. This work is supported by the Deutsche Forschungsgemeinschaft (SFB 341).

- [1] D. Dimos, P. Chaudhari, and J. Mannhart, Phys. Rev. B **41**, 4038 (1990).
- [2] R. Gross, in *Interfaces in Superconducting Systems*, S. L. Shinde and D. Rudman eds, Springer-Verlag, New York (1994), pp. 176-209; see also R. Gross et al., IEEE Trans. Appl. Supercond. **7**, 2929 (1997).
- [3] A. Beck, O. M. Fröhlich, D. Kölle, R. Gross, H. Sato, and M. Naito, Appl. Phys. Lett. **68**, 3341 (1996).
- [4] M. Kawasaki, E. Sarnelli, P. Chaudhari, A. Gupta, A. Kussmaul, J. Lacey, and W. Lee, Appl. Phys. Lett. **62**, 417 (1993).
- [5] R. Gross and B. Mayer, Physica C **180**, 235 (1991).
- [6] A. Marx, L. Alff, and R. Gross, IEEE Trans. Appl. Supercond. **7**, 2719 (1997).
- [7] R. Gross, P. Chaudhari, M. Kawasaki, and A. Gupta, Phys. Rev. B **42**, 10735 (1990).
- [8] D. J. Van Harlingen, Rev. Mod. Phys. **67**, 515 (1995).
- [9] J. Mannhart, H. Hilgenkamp, B. Mayer, C. Gerber, J. R. Kirtley, K. A. Moler, and M. Sigrist, Phys. Rev. Lett. **77**, 2782 (1996); see also Phys. Rev. B **53**, 14 586 (1996).
- [10] Q. Huang, J. F. Zasadzinski, N. Tralshawala, K. E. Gray, D. G. Hinks, J. L. Peng, and R. L. Greene, Nature **347**, 369 (1990).
- [11] D. H. Wu, J. Mao, J. L. Peng, X. X. Xi, T. Venkatesan, R. L. Greene, and S. M. Anlage, Phys. Rev. Lett. **70**, 85 (1993).
- [12] A. Andreone, A. Cassinese, A. Di Chiara, R. Vaglio, A. Gupta, and E. Sarnelli, Phys. Rev. B **49**, 6392 (1994).
- [13] L. Alff, A. Beck, A. Marx, S. Kleefisch, T. Bauch, H. Sato, M. Naito, G. Koren, and R. Gross (unpublished).
- [14] M. Naito and H. Sato, Appl. Phys. Lett. **67**, 2557 (1995).
- [15] H. Yamamoto, M. Naito, and H. Sato, Phys. Rev. B **56**, 2852 (1997).
- [16] V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **22**, 1364 (1969).
- [17] R. Gross, P. Chaudhari, D. Dimos, A. Gupta, and G. Koren, Phys. Rev. Lett. **64**, 228 (1990).
- [18] presuming a highly anisotropic s -wave OP for NCCO, $V_g \simeq \Delta_0/e$ is expected instead of $V_g \simeq 2\Delta_0/e$.
- [19] L. Alff, H. Takashima, S. Kashiwaya, N. Terada, T. Ito, K. Oka, M. Koyanagi, and Y. Tanaka, in *Advances in Superconductivity IX*, S. Nakajima and M. Murakami eds, Springer-Verlag, Tokyo (1997), p. 49.
- [20] M. Naito, H. Sato, and H. Yamamoto, Physica C **293**, 36 (1997).
- [21] O. M. Fröhlich, P. Richter, A. Beck, R. Gross, and G. Koren, J. Low Temp. Phys. **106**, 243 (1997); see also IEEE Trans. Appl. Supercond. **7**, 3189 (1997).
- [22] K. K. Likharev, *Dynamics of Josephson Junctions and Circuits*, Gordon and Breach, New York (1986).
- [23] S. Schuster, R. Gross, B. Mayer, and R. P. Huebener, Phys. Rev. B **48**, 16172 (1993).